TRAVELING WAVE EFFECTS ON NONLINEAR SEISMIC BEHAVIOR OF CONCRETE GRAVITY DAMS

H. Mirzabozorg[1], M. R. Kianoush[2] and M. Varmazyari[3]

[1,3]*Assistant Professor and Graduate Student respectively, Department of Civil Engineering, KN-Toosi University of Technology, Tehran, Iran, email: mirzabozorg@kntu.ac.ir*
[2]*Corresponding Author, Professor, Department of Civil Engineering, Ryerson University, Toronto, Canada,* kianoush@ryerson.ca

ABSTRACT:

In evaluating the earthquake performance of concrete dams, it is evident that the manner in which earthquake ground motions excite the dam-reservoir system is of major importance. In the current article, the effect of partial variation in input excitation on the nonlinear seismic response of concrete gravity dams is considered including the effect of dam-reservoir interaction. The foundation environment beneath the dam body is assumed to be rigid for simplicity and the compressible fluid domain is modeled using fluid elements. The damage mechanics approach is utilized to model the tensile weakness of mass concrete. The exciting ground motion is varied linearly along the base nodes of the dam body considering various propagation velocities. The Pine Flat dam is chosen as a case study. It is found that when the excitation of the system is non-uniform at the base nodes, the patters of the principle stress contours and also, crack profiles are different in comparison with the case under the uniform excitation. In addition, the maximum tensile stresses and the crest displacements are higher in the case when the excitation is non-uniform. It can be concluded that the effect of traveling wave can be significant in seismic safety evaluation of existing concrete dams.

KEYWORDS: Concrete gravity dam, Dam safety evaluation, Dam-reservoir Interaction, Nonlinear behavior, Traveling wave

1. INTRODUCTION

Generally, in seismic safety evaluation of dams, the system is excited uniformly. However, in infrastructures with extended foundations such as concrete dams, the seismic excitation is non-uniform due to limited velocity of earthquake waves and coherency effects. Whether the effect of input variation is significant in the seismic response of the structure or not, clearly depends on the size of the structure-foundation interface. The lag time in the structure support excitation due to finite velocity of seismic wave is called asynchronous.
Seismic safety evaluation of dams is a major task in the field of dam engineering and assessment of nonlinear response of dams in seismic safety evaluation of existing dams can lead to important results and decision making. Bayraktar et al. (1996) investigated asynchronous dynamic analysis of dam-reservoir-foundation systems using lagrangian approach. They showed that the response of the dam is increased due to reducing the wave velocity. Seismic response of concrete-faced rock-fill (CFR) dams subjected to asynchronous base excitation is determined by Bayraktar et al in 2005.
Several researchers have worked on the nonlinear behavior of concrete gravity dams under the static and dynamic excitation using various numerical models which has been reported by Mirzabozorg et al. (2007). However, there is not many works considering the effects of asynchronous on the nonlinear seismic behavior of dams. Alves (2006) considered the effects of spatially variation on the nonlinear seismic response of Pacoima dam. According to the results, the extent of cracking is less severe if the time delay is omitted. Both the number and size of cracks decreased when the system was excited uniformly.

In the present paper, the non-uniform excitation is applied on the system of dam-reservoir. The nonlinear behavior of the mass concrete in 2D space is modeled using damage mechanics approach and validity of the numerical solution method is considered using available academic programs.

2. ASYNCHRONOUS INPUT

It is assumed that the heel of the dam body is excited at first, as shown in Figure 1. The wave propagation is towards the downstream. Therefore, different points along the interface are excited using various acceleration values at the same time which depend on the velocity of travelling seismic waves and the distance of the considered node and the heel of the dam body (Figure 1).

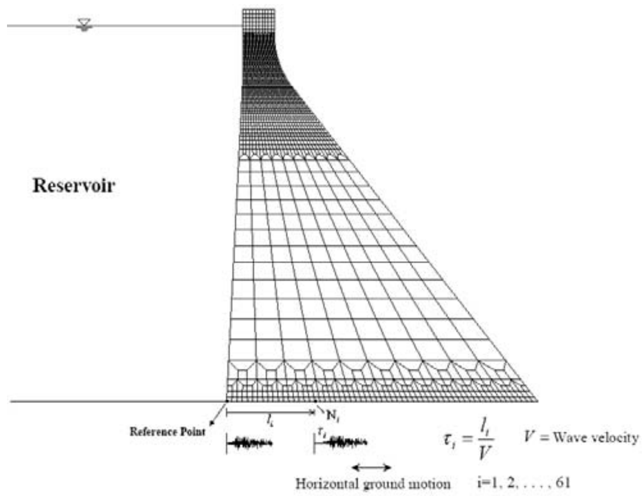


Figure 1: Multiple support excitation

In Figure 1, τ_i is arrival time of the ground motion at the specific support node, N_i; l_i is the distance of the reference node and the node N_i; and V is the travelling wave velocity which is taken as 600 m/s and infinity, in the conducted analyses.

3. DAMAGE MECHANICS

In iso-thermal conditions, the internal damage is defined using an internal variable called the damage variable. Physically, the internal damage is cumulative of micro-cracks in a representative volume. The concrete damaged plasticity model in ABAQUS (2004) has the following characteristics:

- Uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete
- Can be used for plain concrete
- Is designed for applications in which concrete is subjected to monotonic, cyclic, and/or dynamic loading
- Allows user control of stiffness recovery effects during cyclic load reversals
- Can be defined to be sensitive to the rate of straining

Figure 2 illustrates a uni-axial load cycle assuming the default behavior.

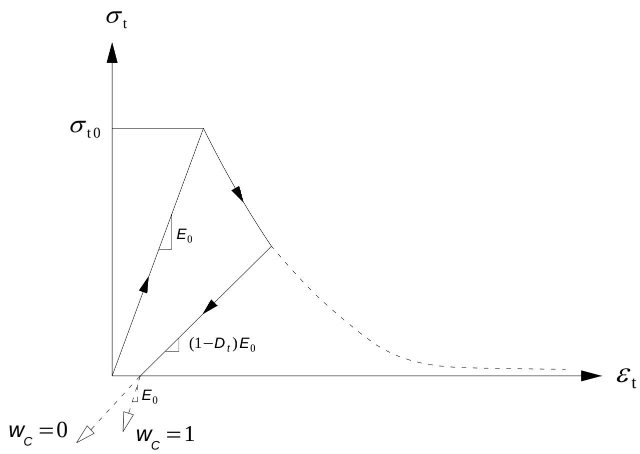


Figure 2: Effect of the compression stiffness recovery parameter w_c

4. FLUID-STRUCTURES INTERACTION

The governing equation in the reservoir media is Helmoltz equation obtained from Euler's equation given as:

$$\nabla^2 p = \frac{1}{C^2}\frac{\partial^2 p}{\partial t^2} \tag{1}$$

where, *p*, *C* and *t* are the hydrodynamic pressure, pressure wave velocity in the liquid and time, respectively. Boundary conditions required applying on the reservoir medium to solve Eqn. (1) are explained in Mirzabozorg et al. (2007) and are not illustrated further herein.

5. CASE STUDY-PINE FLAT DAM

The tallest monolith of Pine Flat dam is selected for considering the effect of spatially variation on the seismic response of the system. The crest of the dam is 560m long and the height of the tallest monolith is 122m. The modulus of elasticity, the unit weight and Poisson's ratio of the concrete are taken as 27580MPa, 2400kg/m^3 and 0.2, respectively. The tensile strength of the concrete is assumed 2.7MPa which is 10% of the compressive strength.

The stiffness proportional Damping equivalent to 10% of the critical damping is applied on the equation of motion of the structure. The structure is modeled using 2040 4-node iso-parametric plane stress elements and 3774 4-node elements produce the finite element model of the reservoir in ABAQUS. Figures 3 and 4 illustrate the dimensions and the finite element models of the dam body and its reservoir, respectively.

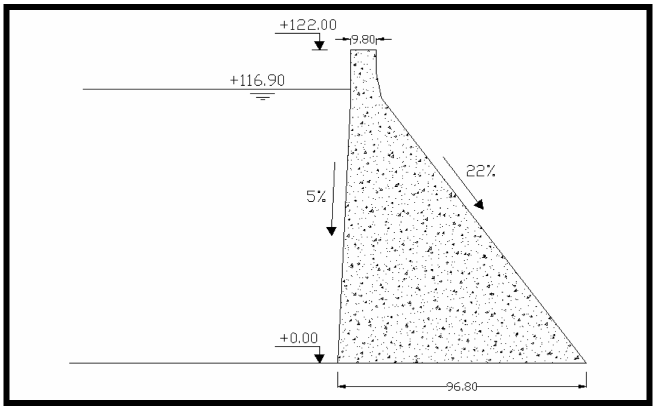


Figure 3: Geometric properties of the dam body-Pine Flat dam

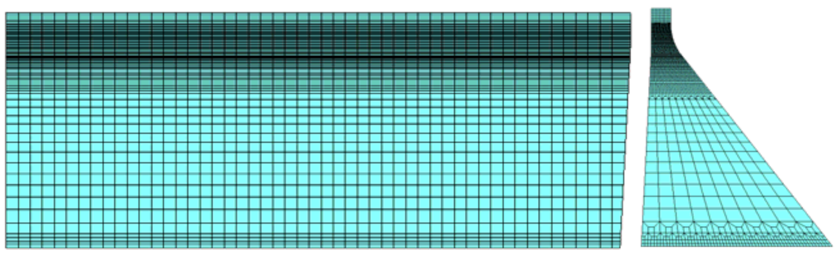
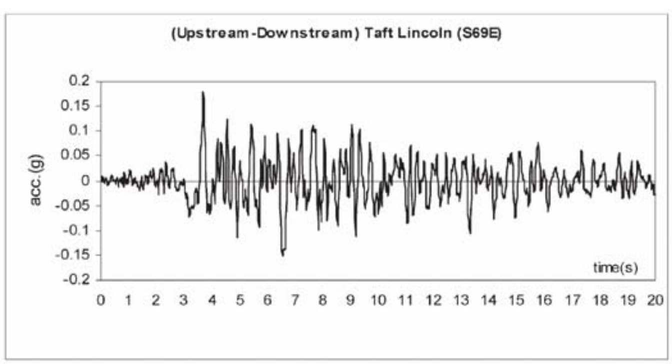


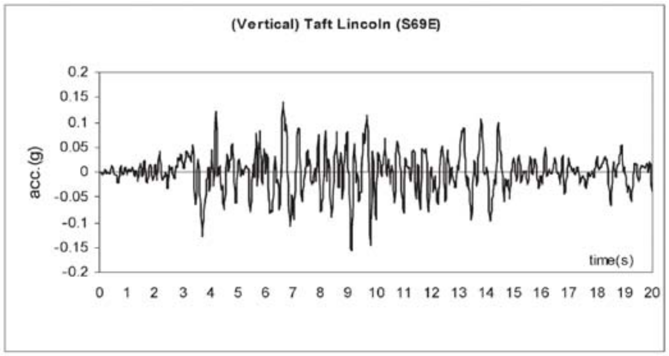
Figure 4**:** Finite element model of the dam body and its reservoir

The length of the FE model of the reservoir is about 2.6 times of the dam body height and the depth of the reservoir is 116.88 m. For the reservoir, the pressure wave velocity and the mass density are taken as 1438.66 m/sec and 1000 kg/m^3, respectively and no absorption is considered at the reservoir bottom.

The first 20 sec. of the earthquake components recorded in Kern County site due to Taft Lincoln earthquake on 21 July 1952 depicted in Figure 5 is used to excite the dam. The components have the PGA equal to 0.179g and 0.155g in horizontal and vertical directions. The time step of the records is 0.02 sec. which is equal to the time step of the seismic analysis.



(a) Stream component



(b) Vertical component

Figure 5: Upstream -downstream (S69E) and vertical components-Taft Lincoln earthquake

5.1. Non-Uniform Excitation Using Stream and Vertical Components

The time history of the crest displacement in the stream and vertical directions for the cases of uniform and non-uniform excitation are given in Figures 6 and 7. As shown, non-uniform excitation increases the crest displacements in the stream and vertical directions. Tensile damage for the cases of uniform and non-uniform excitation is shown in Figure 8. It must be mentioned that there is not any damage within the dam body when the reservoir is empty and the excitation is uniform.

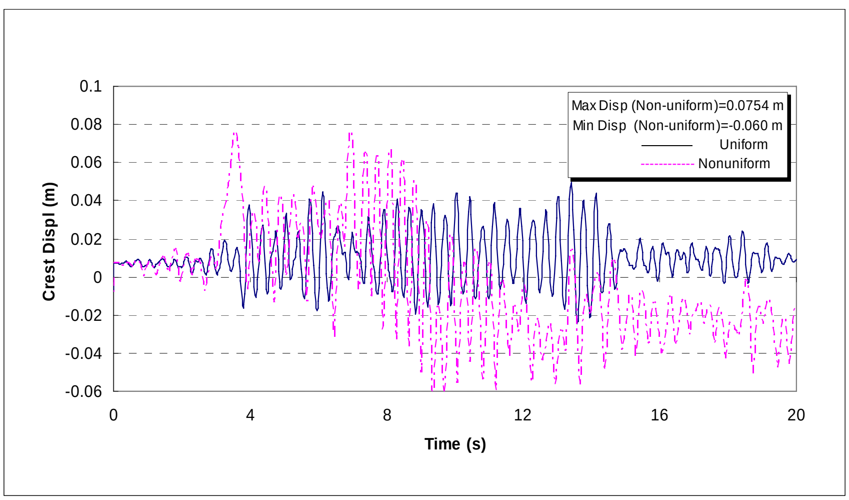


Figure 6: Crest displacement in the stream direction

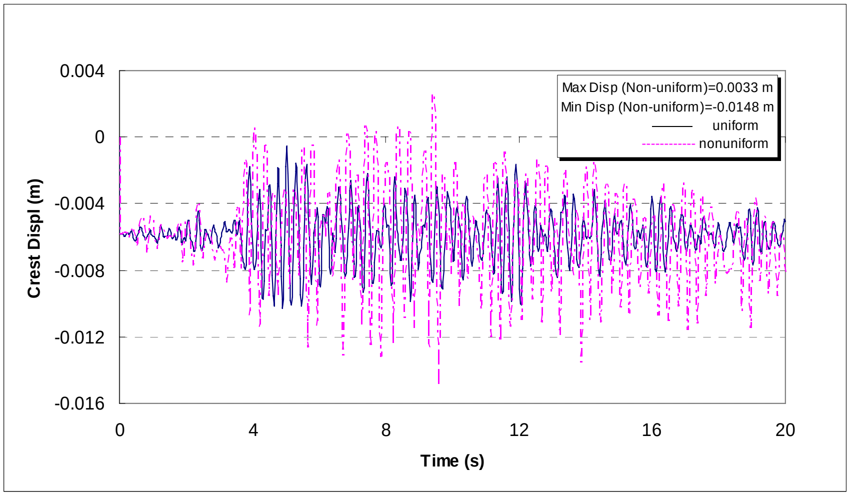
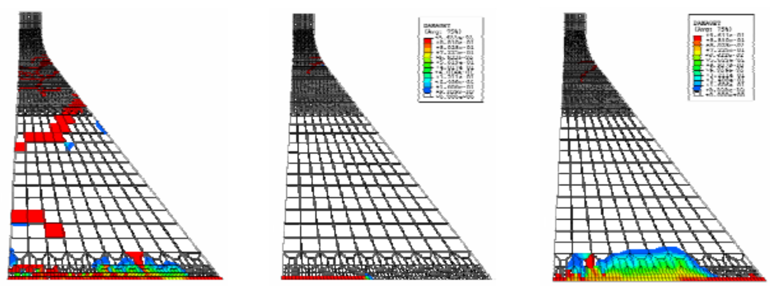


Figure 7: Crest displacement in the vertical direction



(a) (b) (c)

Figure 8: Tensile damage profiles; (a) full reservoir, non-uniform excitation (b) full reservoir, uniform excitation; (c) empty reservoir, non-uniform excitation

Clearly, both the extension and the number of cracked elements within the neck region and near the base of the dam body increase intensely when the system is excited non-uniform with seismic wave propagation velocity of 600 m/sec. To obtain reasonable results in the design of the concrete gravity dams, the shear wave velocity used in the dynamic analysis of the dam should be taken from the experimental studies conducted on the dam site.

5.2. Non-Uniform Excitation Using Stream Component

The time history of the crest displacement in the stream and vertical directions for the cases of uniform and non-uniform excitations are given in Figures 9 and 10, respectively. Figure 11 shows the contours of the tensile damage of the dam body. There is not any crack profile within the dam body when the reservoir is empty and the excitation is uniform.

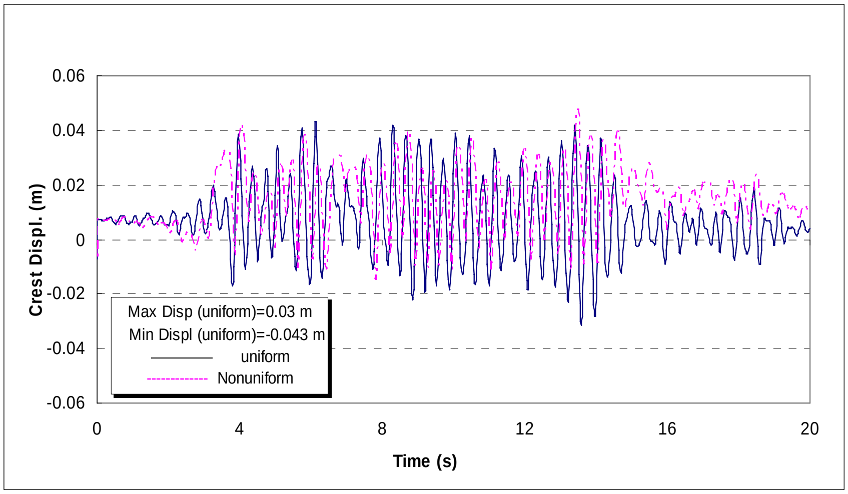


Figure 9: Crest displacement in the stream direction due to horizontal excitation

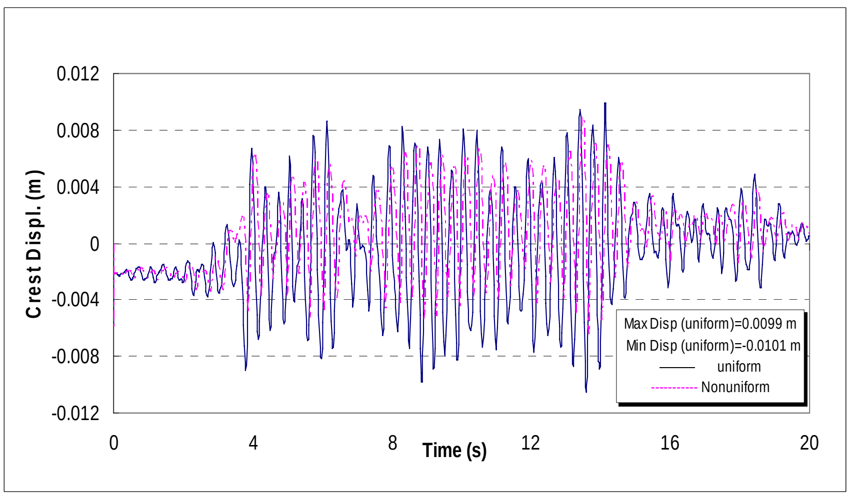
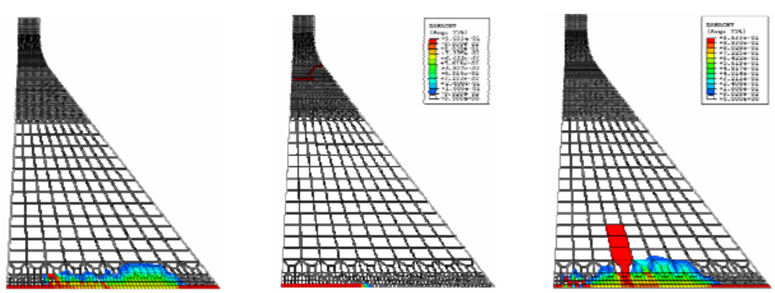


Figure 10: Crest displacement in the vertical direction due to horizontal excitation



(a) (b) (c)

Figure 11: Tensile damage profiles; (a) full reservoir, non-uniform excitation (b) full reservoir, uniform excitation; (c) empty reservoir, non-uniform excitation

Obviously, the extension and the number of crack profiles near the base of the dam increase considerably, when the excitation is non-uniform. In addition, in the case under both the horizontal and vertical excitation, non-uniform excitation of the system increases intensely the crest displacements and crack profiles within the neck region of the dam body in comparison with the uniform excitation.

6. CONCLUSIONS

A nonlinear seismic analysis of concrete gravity dams with spatially variation ground motion including dam-reservoir interaction is conducted. The reservoir-structure interaction effect is accounted for using finite element method assuming the reservoir is compressible. Isotropic damage mechanics approach is applied for modeling the nonlinear behavior of mass concrete in 2D space. The system of dam-reservoir is excited non-uniformly due to limited seismic wave propagation velocity. The two sets of wave propagation velocities used in the conducted analyses are taken as 600 m/sec and infinity. The Pine Flat dam is chosen as the case study.

Generally, the tensile damage near the base of dam body increases intensely, when the excitation is non-uniform. In addition, when the system is excited in both horizontal and vertical directions, the crest displacement increases and the tensile damage within the neck region of the dam body is more extensive in comparison with the case under the uniform excitation.

For the system of dam body with the empty reservoir, there is not any crack profile when the uniform excitation is applied on the system. However, when the system is excited non-uniformly, considerable tensile damage occurs near the base of dam.

The results show that the non-uniform excitation can lead to crest displacement and crack profiles which, is different from those obtained under the uniform excitation. Therefore, the effect of non-uniform excitation must be considered in dam design and dam safety evaluation based on the site and structural conditions.

REFERENCES

ABAQUS /Standard (2004), Finite Element Program, Hibbit, Karlson & Sorenson, Inc, Providence, R.I.

Alves, S.W. Hall, J. F. (2006). Generation of Spatially Non-uniform Ground Motion for Nonlinear Analysis of a Concrete Arch Dam. *Earthquake Engineering & Structural Dynamics* **35:11**, 1339-1357.

Bayraktar, A., Dumanoglu, A.A. and Calayir, Y. (1996). Asynchronous Dynamic Analysis of Dam-Reservoir-Foundation Systems by the Lagrangian Approach. *Computers and Structures* **58:5**, 925-935, (SCI).

Bayraktar, A., Haciefendioglu, K. and Muvafik, M. (2005). Asynchronous Seismic Analysis of Concrete-Faced Rockfill (CFR) Dams Including Dam-Reservoir Interaction. *Canadian Journal of Civil Engineering* **32:5**, 940-947. (SCI).

Ghaemian, M. and Kianoush, R. (2001). NSAG-DRI: A Computer Program for Nonlinear Seismic Analysis of Concrete Gravity Dams Including Dam-Reservoir Interaction.

Lee, J. Fenves, G.L. (1998). Plastic-Damage Model for Cyclic Loading of Concrete Structures. *Journal of Engineering Mechanics* **124:8**, 892–900.

Mirzabozorg, H., Ghaemian, M., Noorzad, A. and Abbasi Zoghi, M. (2007). Dam Reservoir-Foundation Interaction Effects on Nonlinear Seismic Behavior of Concrete Gravity Dams Using Damage Mechanics Approach. *International Journal of Earthquake Engineering and Engineering Seismology* (EEE). **3**, 52-60.